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OPTIMIZING HYBRID PLATE FIXATION WITH A LOCKED, OBLIQUE END SCREW IN OSTEOPOROTIC FRACTURES

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ABSTRACT

BACKGROUND: The end screw in a fracture plate creates the greatest resistance to bending. For osteoporotic fractures treated with plates, there is some question as to the optimal screw insertion technique for the screw farthest from the fracture. A locked, oblique end screw was previously shown to increase resistance to periprosthetic fracture. It is unknown, however, how this end screw configuration would resist pullout when subjected to bending.

METHODS: Narrow, low contact 3.5 mm locking compression plates with 6 and 12 holes were anchored to simulated bone material with material properties representing osteoporotic bone. Four configurations were evaluated for the end screw: perpendicular and angulated 30 degrees away from the fracture for both non-locked and locked screws (n=6 per group). The constructs were subjected to 3 point bending until the peak load and finally total construct failure was achieved.

RESULTS: Peak force, stiffness, energy to peak load, and the failure mode of each construct were determined. All four 12-hole construct groups failed by gross plastic bending deformation of the plate at the fulcrum past a previously established clinically relevant limit for failure (15°). All 12-hole plate constructs failed at statistically higher loads and energy than any of the 6-hole plate constructs, with the exception of the 6-hole locked, oblique construct.

CONCLUSION: The locked, oblique end screw provides equivalent pull out strength for 3.5 mm low contact plates regardless of plate length. Combined with its resistance to periprosthetic fracture, this end screw configuration appears to be the best option for the construct integrity of hybrid plating for osteoporotic fractures.

CLINICAL RELEVANCE: Osteoporotic fractures are challenging to treat. The current study and the existing literature show that resistance to both bending loads and refracture at the end of a plate are minimized with a locked screw angled away from the fracture.

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INTRODUCTION

Osteoporosis has a significant role in fractures of the elderly, contributing to 75% of fractures caused by low energy mechanisms.[1] In 2010, 10 million people had osteoporosis in the United States with more than 2 million fractures related to osteoporosis or osteopenia annually.[2] The weakened bone presents difficulties with fixation, including failure of plate fixation. One mode of non-locked plate failure includes the sequential pull out of screws starting with the end screw.[3] This failure mode has been attributed to bending loads;[4] such loading is a common mechanism for the initial injury as well.[5] Since non-locked plate fixation relies on the screw to bone fixation to compress the plate to the bone, failure of screw fixation leads to catastrophic failure of the construct.[3,6] Given its lower density, osteoporotic bone is at risk for this mode of failure since it cannot withstand significant insertion torque and the potential for stripping of the screws is increased.[7,8] In addition, the quality of bone is an important factor in the pull out strength of a screw.[1,9] To strengthen construct fixation in osteoporotic bone, both the length of the plate and number of screws have been shown to increase the strength of the construct.[10,11,12] Inserting the end screw at an angle away from the fracture has also been shown to increase the resistance to screw pullout.[4,13]

The introduction of locked plates was seen as a potential solution for many of the problems associated with osteoporotic fractures.[14] As the screw heads purchase into the plate holes, a fixed angle is created and obviates the need for plate to bone compression.[3] The fixed

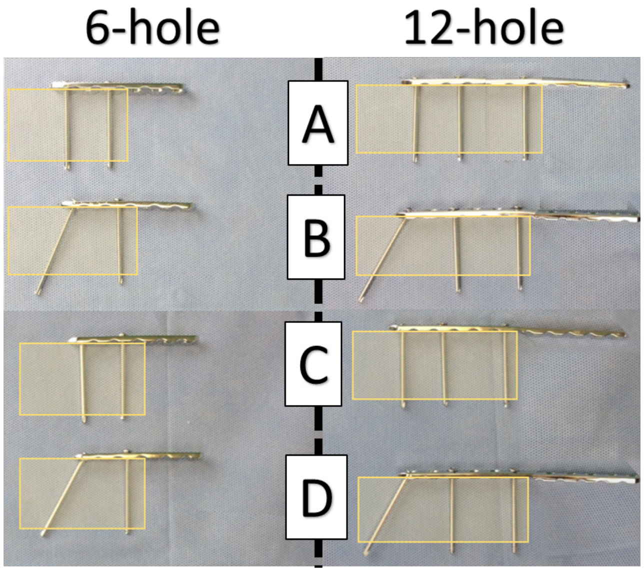

Figure 1. Six and 12-hole plates were used to evaluate 4 different end screw configurations: non-locked, perpendicular (A), non-locked, oblique (B), locked, perpendicular (C), and locked, oblique. The rectangles represent the size and position of the bone blocks which exhibited the material properties of osteoporotic bone.

angle construct does not require the high insertional torque of screws needed in conventional plating, making locked plating an effective tool in osteoporotic bone that is unable to accommodate such torque.[3,7] That said, the benefits of locked plating in osteoporotic bone have not translated into obvious superiority over conventional plating across all fractures.[15,16,17] Though increased stability has been the goal of many biomechanical studies and novel constructs, excessive stability can lead to stress shielding.[10] The lack of a sufficient magnitude of interfragmentary motion can inhibit bone healing, create a nonunion, and, ultimately, a fatigue failure of implant.[18] Hybrid plating sought to combine aspects of locked and conventional plating to address the drawbacks of the use of an all-locked plate.[19,20,21] Non-locked screws are first used to reduce the fracture to the plate and locked screws are used to increase the construct's stability.[22]

With hybrid plating techniques, details regarding the optimal screw type and orientation are somewhat unclear, particularly with regards to the screw farthest from the fracture and often in the end of the plate. After the introduction of locked plates, periprosthetic fractures occurring through the end screw were a concern.[23,24,25] This is not surprising in light of data which shows that the bone stresses are greatest at the end hole.[26,27] Bottlang et al. suggested that a non-locked screw at the end of a plate created a more gradual transition between the plate and bone.[25] This construct was significantly more resistant to peri-plate fracture than an all locked construct. Peck et al. showed that additional fracture resistance could be attained with a hybrid plate that used non-locked inboard screws and a locked end screw angled away from the fracture.[28] While all fractures still occurred through the end hole, the increased fracture resistance was attributed to two factors. First, there were more screw threads engaged in the oblique hole and thus more bony tissue had to fail versus a perpendicular hole. In addition, the fixed angle feature of the end screw augmented implant stability to produce higher failure loads and failure energy.[28] While the locked, oblique end screw provided the greatest resistance to peri-plate bone fracture, the influence of this technique on screw pullout resistance is unknown.

The objective of the current study was to evaluate non-locked and locked end screws in both perpendicular and oblique orientations in loading to determine construct pullout strength. The constructs were thus subjected to 3 point bending. More specifically, it was hypothesized that the locked, oblique end screw would have the greatest pull out strength. The data from the current study was then compared to companion studies using the same test methodology to propose guidelines for screw insertion techniques in osteoporotic bone.

METHODS

The experiment design and test rig were adapted from the literature.[4] A polyurethane foam model (model 1522-01; Pacific Research Laboratories, Vashon Island, Washington) with osteoporotic properties (=0.16 g/cm3) was utilized as it limited inter-sample and intra-sample variability. The number of samples per plate construct (n=6) was based on previous literature and confirmed with a power analysis.[4] Eight different plate constructs were tested for a total of 48 specimens (Figure 1). All plates and screws were 3.5 mm and constructed of 316L stainless steel. Twenty four plates were stock, commercially available low contact compression plates and 24 were modifications of the commercial plate (VOI; models 3.506 LCCP, 3.512LCCP, and custom; Florida). In all stock plates, all holes were non-locked and designed for non-locked screws. In these plates, the end screw was either placed perpendicular or angled 30^{o} away from the fracture site (Figures 1, 2). In the custom plates, the inboard holes were also non-threaded, however, the end hole was modified with a locked hole. This locked end hole was designed for either a perpendicular, locked screw or an oblique, locked screw angled 30^{o} away from the fracture site.

In all constructs the inboard screws were non-locked and tightened to 300 N-mm of torque based on pilot testing that indicated this torque was 75% of the minimum torque required to strip the 3.5 mm screw in the

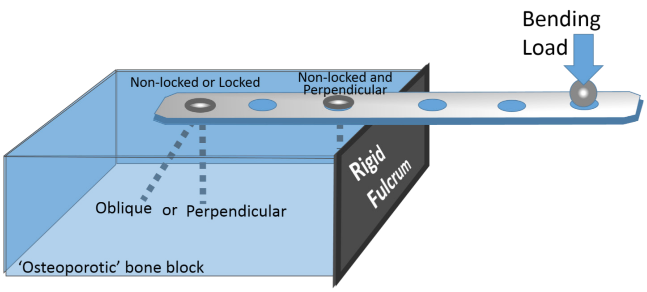

Figure 2. A bending load was delivered to the third hole from a rigid fulcrum for all tests. A rigid fulcrum prevented crushing damage to the bone block to focus the failure to either the end screw or plate. Only the end screw varied for the four groups, the inboard screw(s) was perpendicular and non-locked for the 6 hole (shown) and 12 hole plate groups.

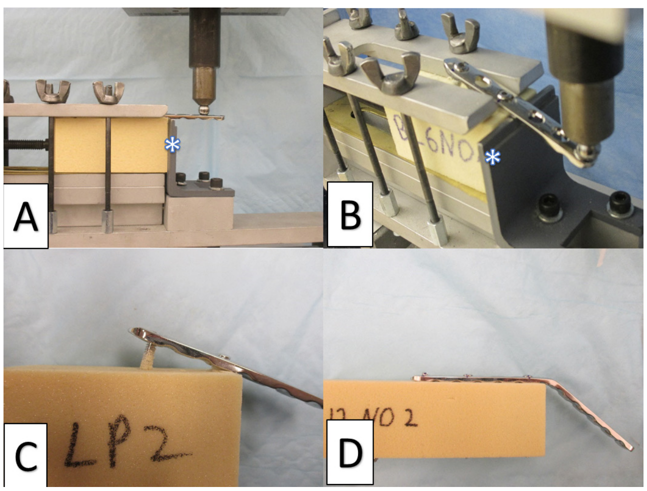

Figure 3. The testing rig (A) subjected the constructs to 3 point bending until failure of the construct (B). The plates failed by screw pullout (C: 6-hole) and plastic deformation (D: 12-hole). (* A rigid fulcrum prevented crushing damage to the bone block to focus the failure to either the end screw or plate.)

osteoporotic bone block.[29] To isolate the effect of the end screw, all inboard screws were identical. Screws were placed after drilling pilot holes of 2.5 mm and 2.8 mm for non-locked and locked screws, respectively, in compliance with manufacturer and literature guidelines.[30] The non-locked, perpendicular end screw groups served as controls for each plate length, as this construct was previously used it allows for comparison to prior literature. The three remaining groups described above served as three test groups by altering the end screw implantation parameters: 30^{o} angulated non-locked, perpendicular locked, and 30^{o} angulated locked.

The constructs were evaluated in cantilever gap closing three point bending with a materials testing machine (Figure 3, Test Resources 8304, Shakopee MN). A hardened steel sphere attached to the test machine's actuator delivered the bending load to the third cantilevered hole (Figure 2, 3) of each plate.[29,31] The construct was attached to a mobile carriage to ensure the load remained centered in the plate hole as the plate rotated about a rigid fulcrum.[4] The bending load was delivered with the actuator in position control mode (0.3 mm/second) until failure of the construct was observed.[32, 33] Failure for all 6-hole plates was observed to be a gradually increasing load which peaked just prior to loss of stable fixation of the end screw. The load then dropped acutely; the test was allowed to continue until the end screw was grossly loosened from the artificial bone block. Following failure, all 6-hole constructs continued to resist the continuing deformation as the actuator continued to move downward. The post-failure load was documented for all 6-hole constructs. In contrast, the 12-hole plates plastically deformed in bending such that the load continued to increase without a loss of fixation of the end screw. To establish a threshold for failure, the limit for clinically acceptable bone angulation was considered. The 3.5 mm plate used in the current study would be suitable for fixation of the forearm. Prior studies have shown that angulation of ~15^{o} represents a limit above which there would be interference to pronosupination.[34,35,36,37] Thus, in the current study, angulation of the plate greater than 15^{o} was considered a failure even though the screws were still intact. Evaluation of plate deformation or damage to surrounding bone was performed via visual inspection by two observers. The load data was recorded by a transducer (Model M211-119, Test Resources, Shakopee, MN, Resolution = 1N) attached to the machine actuator. Displacement of the cross head was recorded by a transducer (LVDT, Test Resources, Shakopee, MN, Resolution = 0.01 mm). All data were sampled at 30 Hz.

The bending load versus displacement was used to determine the peak load, stiffness, and the energy to failure. As noted above, the 6-hole plates were observed to have a focal, readily identifiable peak load which correlated with loss of stability for the end screw. The area under the load-displacement curve prior to this peak load was taken as the energy to failure. In contrast, for the 12-hole plate, the peak load was taken as the load that occurred when the plate had grossly deformed 15°. The energy was likewise calculated to this same peak load. For both length plates, the stiffness was taken as the slope of the linear portion of the curve (R2>0.99 for all constructs). The data from the eight groups were compared using an ANOVA with Student-Newman-Keuls post-hoc testing (SigmaStat, SPSS) after confirming normal distribution of data (= 0.05). In cases of non-normal data, ANOVA on ranks was used.

Figure 4. Close inspection of the failed 12-hole perpendicular, non-locked plates revealed that the plate bent at the rigid fulcrum such that an arc extended over the bone block. Compared to the gross bending of the plate concentrated at the fulcrum, this more subtle arc lifted the plate off the bone block and pulled out the two screws proximal to the fulcrum. This phenomenon was not observed in the other 12 hole groups.

RESULTS

For all 6-hole plates, construct failure resulted in screw pullout without gross deformation of the plate (Figure 3). In contrast, all 12-hole plates failed by plastically deforming past the 15o threshold.[34,35] In the 12-hole non-locked, perpendicular end screw constructs, the screws closer to the fracture pulled out of the bone slightly as the plate bent into an arc shape centered over the fulcrum (Figure 4), however, this occurred after the plate had surpassed the 15o deformation limit.

There was a trend for the locked, oblique construct to exhibit the highest peak to load failure of any 6-hole plate (Table 1), which was significantly stronger when compared to the non-locked, perpendicular construct. The 6-hole non-locked, oblique construct also had a significantly higher load to failure than the non-locked, perpendicular construct (Figure 1). All of the 12-hole constructs had significantly greater loads to failure than all of the 6-hole constructs, except for the 6-hole locked, oblique construct. While there was a trend for the locked oblique 12 hole construct to exhibit the most robust performance, none of the 12 hole groups differed significantly from the other 12 hole groups for all data.

There were no significant differences for stiffness within each plate length subgroup. There was a trend or significant difference for all 12-hole groups to be less stiff than all of the 6-hole groups. The energy to failure for all 12-hole plates was greater than the 6-hole groups except the 6-hole locked, oblique design. In general, the 12-hole plate failure energies were 2 to 3 times magnitudes of the 6-hole non-locked and perpendicular locked groups. In contrast, the 6-hole locked, oblique construct energy magnitudes were only ~20% lower than the failure energies from the 12 hole groups.

The 6-hole plates demonstrated a post-failure phenomenon in which the constructs continued to provide resistance to the advancing machine actuator after the peak load was achieved (Figure 5, Table 2). The maximum post-failure loads for the locked constructs were approximately twice as great as the non-locked groups. As a percentage of the peak load, the locked constructs were able to resist the moving actuator with loads which were 81-87% of the peak failure load. In contrast, the non-locked constructs' post-failure loads were significantly less at 36-56%.

Table I.

Plate length	End Screw Orientation (See Figure 1)	Peak Load (N)	Stiffness (N/mm)	Energy to Peak load (N-mm)
6 Hole	6A: Non-locked, perpendicular	343±50	111±7	588±164
	6B: Non-locked, oblique	429±40*	124±13	902±283
	6C: Locked, perpendicular	399±37	111±7	834±192
	6D: Locked, oblique	470±58*	119±5	1,250±512*
12 Hole	12A: Non-locked, perpendicular	499±49*@	100±9#&	1,560±346*#@
	12B: Non-locked, oblique	480±42*@	101±15#&	1,469±417*@
	12C: Locked, perpendicular	490±23*@	98±5#&	1,522±205*#@
	12D: Locked, oblique	516±12*#@	104±6	1,656±165*#@

Table 1. Four different end screw configurations were evaluated for 6- and 12-hole plates in 3 point bending until failure of screw fixation was achieved. The plates were attached to bone blocks representing osteoporotic bone.

*** Significantly different than Group 6A**
 # Significantly different than Group 6B
@ Significantly different than Group 6C
& Significantly different than Group 6D
None of the 12 hole plate groups were significantly different from the remaining 12 hole groups

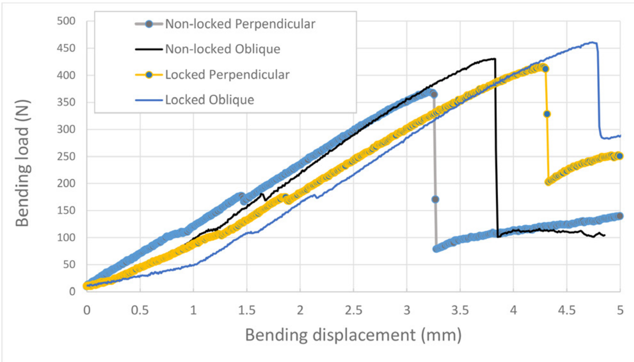

Figure 5. For all 6-hole plates, a post-failure phenomenon was observed in which the construct continued to resist load after the peak load was achieved. The test was allowed to continue following the peak load and the post-failure load was determined. Locked end screws exhibited post-failure loads which were nearly as great as the failure loads (Table 2).

Table II.

End Screw Orientation for 6-hole plates (see Figures 1)	Average Post Failure Peak Load (N) (see Figure 4)	Normalized post Failure Peak Percentage
A: Non-locked, perpendicular	187±19	56% ± 11%#
B: Non-locked, oblique	150±34	36% ± 10%*
C: Locked, perpendicular	320±10*#	81% ± 8%*#
D: Locked, oblique	406±21*#@	87% ± 9%*#

Table 2. Following the peak bending load, the 6-hole plate constructs maintained a post-failure phenomenon in which the load did not diminish to zero. Rather, the constructs continued to provide resistance to continued bending at lower load than the peak magnitude (see Figure 4). The normalized peak is a ratio of the post-failure peak load to the peak load for initial failure (Peak Load in Table 1).

*** Significantly different than Group A**
 # Significantly different than Group B
@ Significantly different than Group C
& Significantly different than Group D

DISCUSSION

The current study compared the construct strength of four plate constructs with the following end screw configurations: non-locked in perpendicular and 30° oblique orientations, and locked in the same orientations. All four constructs were tested in osteoporotic bone models in 3 point bending with 6-hole and 12-hole 3.5 mm low contact compression stainless steel plates.

In the current study all 6-hole constructs failed via pullout of the end screw with no gross deformation of the plate. The 12-hole constructs all failed via gross plastic bending of the plate with no loss of fixation of the end screw. Somewhat surprisingly, the failure loads of the 6-hole plates were lower, but similar to the load for the 12-hole plates at 15° of bending. The magnitude of angular deformation was used as a threshold to distinguish a plate which could potentially remain functional in a clinical setting (as described earlier). There was a trend for the locked oblique end screw constructs to exhibit the highest peak loads in both 6 and 12-hole groups. However, the 6-hole locked, oblique was significantly greater than only the perpendicular, non-locked controls. The 12-hole plates required significantly more energy to failure than the 6-hole plates, with the notable exception of the 6-hole locked, oblique construct. There was no difference in stiffness between constructs of the same length. In general, the 12-hole plates were significantly less stiff than the 6-hole constructs. A post-failure phenomenon was observed for the 6-hole constructs in which there was a second peak load after failure with the locked constructs sustaining a significantly higher percentage of the load after failure.

In the 6-hole constructs, both locked and non-locked oblique screws had improved pullout compared to the non-locked perpendicular screw. This finding is consistent with previous studies which showed that an oblique end screw increases pull out strength in non-locked plating.[4,29] The locked, oblique end screw constructs for the 6- and 12-hole plates in the current study tended to have the greatest pullout strength and failure energies for the respective plate lengths. Additionally, the 12-hole locked, oblique group did tend to exhibit a greater failure load and failure energy than the 6-hole locked oblique, though this difference was not significant. This outcome is consistent with prior data demonstrating that longer plates are associated with increased pullout strength.[11,10]

By using non-locked and locked screws in the same construct in the hybrid plating technique, previous studies have demonstrated improved periprosthetic fracture resistance compared to an all locked plate.[25,24] Additional investigation revealed that a hybrid construct with non-locked inboard screws and a locked, oblique end screw had the greatest resistance to periprosthetic fracture.[28] Non-locked inboard screws allow for compliance with described plating techniques for the first screw in a fragment. It is recommended that the non-locked first screw be placed in an inboard position for hybrid constructs.[21,19] The current study shows that the hybrid construct with a locked oblique end screw is equivalent or stronger than the conventional construct in regards to screw pull out. The optimal end screw would therefore be a locked, oblique screw employed in a hybrid construct with non-locked in board screws, as it offers improved resistance to periprosthetic fracture and the best or equivalent pull out strength.

Charpentier et al. used the same experimental method as in the current study and described a post failure phenomenon by which plated constructs maintained some load after failure had occurred.[29] The locked, oblique construct in the current study not only trended toward greater load to failure but also had the highest percentage of this load maintained after failure. More than 80% of the failure load was observed following failure for both locked 6-hole plates with the locked, oblique being superior. Thus, the locked, oblique configuration may offer some residual stability to a failed hybrid plate construct. Clinically, this may translate into a construct that still provides some fixation after failure to prevent a fracture from grossly displacing before revision. Such stability could help limit pain as well as prevent deformity that would be difficult to correct at a subsequent surgery.

A limitation of the current study is that it is concentrated on a single mode of failure, namely 3-point bending leading to screw pullout or plate bending or a combination of the two. This mode was chosen because a previous study already evaluated the same end screw configurations and their influence on bone fracture at the plate ends.[28] Thus, the current study added to those previous findings as to the superior overall performance of an locked, oblique end screw. An additional limitation is related to the plates used in the current study (3.5 mm low contact compression plates) which revealed that the failure data for 6- and 12-hole locked, oblique plates were not significantly different. Additional testing would be needed with smaller and larger plates to determine if this phenomenon holds true with plates of other sizes. It is reasonable to assume that a thicker plate with greater bending resistance would be more likely to fail via screw pull out and not gross bending deformation, as seen in the 12 hole plates in the current study. The hybrid constructs in this study were compared against conventional constructs, as was done in previous studies. Though locked, oblique end screw constructs were shown to be superior to conventional constructs, they were directly compared to only one other hybrid construct, the locked, perpendicular end screw. Testing and directly comparing a greater variety of hybrid constructs to the locked, oblique end screw construct could be done in future studies for various modes of failure. Finally, the current study used bone blocks to represent osteoporotic bone. This method was adopted to reduce the variability of the specimens to aid in isolating any differences caused by the different end screw configurations. Similar studies have used artificial bone for the same reason.[25,24,29,28] That said, caution is warranted in extending the results from the current study to clinical application. For example, only one type of simulated bone was used in the current study to represent osteoporotic bone. Either stronger or weaker bone properties may lead to differing conclusions as to the influence of the end screw.

The data from the current study and the literature suggest that plate fixation of osteoporotic fractures with 3.5 mm low contact compression plates should use a locked, oblique end screw with hybrid fixation of the remaining screws. This construct has equivalent or greater screw pull-out strength when compared with other end screw configurations. Additionally, this design has demonstrated superior resistance to periprosthetic fracture.[28] Further investigations are needed to evaluate constructs of different length or plate design to determine if the locked, oblique end screw is superior in other settings. Fatigue testing the constructs from the current study could further elucidate the mechanical behavior of this design.

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